NREL PV

Working With Industry

Third Quarter, 1998

Getting There

Some fundamental questions lie before us. How *do* we get there? How *do* we speed up our arrival to that day when photovoltaic technologies are everyday commodities, being used virtually everywhere they make sense? To those of us in the PV community—to anyone conscious of the delicate balance between energy use and the environment—that day can't come soon enough.

In part, the answers to these questions can be found in the work described in this issue. The recent National Center for Photovoltaics (NCPV) Program Review Meeting is profiled, wherein researchers, developers, and integrators presented recent accomplishments and progress. Each accomplishment brings us a step closer to getting there.

The simple answer is that we keep working together to make PV technologies cheaper and better. That's the philosophy behind the four National Research Teams of the Thin Film PV Partnership. Articles on two of those teams, CIS (copper indium diselenide) and Cadmium Telluride, appear in this issue. The other two teams, Amorphous Silicon and Environment, Safety, and Health, were profiled in the last issue.

In perusing the articles on the two National Teams, you'll see that members of each team's working groups are getting there by getting specific. They're working on ways to make the technologies manufacturable and usable on a broad scale—which will enable their use by millions, even billions, of people around the world. The work of these problem-solving teams represents giant steps in getting there.

This is what the U.S. Department of Energy PV Program has always been about. And, with PV markets heating up along with the global climate, getting there is getting more interesting all the time.

Features

Departments

The Accomplishments Stand Out

An Editorial by Richard King

NREL/PIX06673

Richard King is Senior Program Manager for Photovoltaics in DOE's Office of Photovoltaics and Wind Technologies. His entire professional life has been devoted to photovoltaics, beginning with stints at Planning Research Corporation and Science Applications International Corporation prior to joining DOE in 1986.

To be honest, I had to do some checking to come up with the number of PV Program Review Meetings I've attended. This year's meeting was the 15th since 1978, and I've been on hand for nine of them. Memories of individual meetings fade away—but the accomplishments stand out.

Our most recent NCPV Program Review Meeting, held September 1998 in Denver, gave us a chance to revisit a PV milestone on its 25th anniversary—the Cherry Hill conference. Cherry Hill is considered by many to be the birth of the National Photovoltaic R&D Program. As a result of that conference and its report to Congress, the seed was planted for the program we are now involved in.

Remember the 1970s? In those days, we were waiting in gas lines and worrying that oil would run out. In response to OPEC holding us hostage, Presidents Nixon and Carter pushed for stronger photovoltaic and renewable R&D programs to make our nation energy independent. Today, the political climate is different. In real costs, oil is cheaper than it has ever been, and OPEC has lost power because lesser-developed countries are flooding the market with oil as they seek petrodollars to fuel their economies. Global climate change and the environment are the important drivers as we approach the new millennium. The one constant through all of this has been the promise photovoltaics holds for a brighter future.

It was a treat to hear Cherry Hill veterans Lloyd Herwig and Richard Blieden describe how the 1973 conferees projected the future of PV. We haven't quite met the ambitious cost goals set then, but we've made some amazing technical progress. Cherry Hill papers discussed the limitations of making 6%–8%-efficient silicon cells, and thin films were just beginning to be explored. What's more, there was hardly any PV industry.

Today, we have a viable PV industry selling over 50 megawatts of modules of all kinds, including four different thin-film technologies.

At this year's meeting, John Geisz and Sarah Kurtz caught my attention with presentations on work directed toward reaching 40% efficiency in a four-junction cell (using III-V materials under concentration). This shows the progress that can be achieved with research—and why we *must* hold fast to our commitment to finish the job.

At the meeting in 1986, the year I joined the Department of Energy, Rommel Noufi reported cell efficiencies of more than 10% for CIS. Now, the record efficiency for CIS cells stands at 17.7%. And, as Bob Wieting told us at this 1998 meeting, the Siemens Solar assembly line is cranking out the first commercial CIS modules.

We also have *new* approaches. I'm thinking of the four Thin Film PV Partnership National Teams, two of which are profiled in this issue. Team members are doing an excellent job of pooling their knowledge and chipping away at the barriers on the path to commercial success for thin-film technologies—and improving the efficiencies, cost-effectiveness, and safety every step of the way. In the Cherry Hill days, thin films were a laboratory curiosity. Today, they are a viable reality. It shows how far we've come.

It has always been a privilege to witness the combined strength of the laboratories, companies, and universities that make up the PV Program—and this year's meeting was no exception. My compliments to all involved, especially General Chair Mowafak Al-Jassim and Co-Chairs James Gee and John Thornton. Here's to the next 25 years—and the new PV advances we can't even imagine now.

Contact Richard King at 202-586-1693

PV Web Sites

DOE PV Program ....*http://www.eren.doe.gov/pv*
About Photovoltaics • News and Information • About Our Program

National Center for Photovoltaics ....*http://www.nrel.gov/ncpv*
World Class R&D • Partnering and Growth • Information Resources

The Center for Basic Sciences ....*http://www.nrel.gov/basic_sciences*
Capabilities • Optoelectronics • Biological Sciences

Measurements and Characterization..*http://www.nrel.gov/measurements*
Virtual Lab • Capabilities • Doing Business • Data Sharing • The Center

Renewable Resource Data Center ....*http://rredc.nrel.gov*
General Information • Information by Resource (Biomass/Solar/Wind)

Million Solar Roofs ....*http://www.MillionSolarRoofs.org*
Initiative Goals • Scope • Solar Technologies

NREL International Programs ....*http://www.nrel.gov/business/international/intl_graphics.html*
Applications • Countries • Supporting Activities

Success Stories
The National CIS R&D Team

Kannan Ramanathan was ebullient. "You get an adrenaline rush when you crack a tough problem in your field. That's why I work at a national lab."

He was talking about the recent triumphs of a working group under his leadership. This group was formed two years ago when the Thin Film PV Partnership's National CIS R&D Team reorganized into four working groups to spur progress in the technology and to actively involve more of its members.

One of the new working groups was established to explore new ways (other than using a cadmium sulfide window layer) to form a junction with the CIS (copper indium diselenide) layer. A second was to explore the role that the molybdenum back contact had in the diffusion of sodium into the CIS layer. The third was to research why some CIS modules were experiencing transient effects—an initial loss of conversion efficiencies, followed by an increase after light soaking. The fourth, Ramanathan's Present Junction working group, was to continue its exploration of the standard CdS/CIS junction.

The Junction Conundrum

Standard CIS devices are made with a CdS window layer, which poses some concerns. CdS is not a perfect window layer; it absorbs some of the blue end of the spectrum, and so does not allow some of the light to reach the CIS absorber layer. Also, the prevailing process used for preparing CdS—chemical bath deposition, or CBD—is a wet-chemistry process; this slow process is not a preferable path for the in-line production used by some companies.

But these were almost side issues to the Present Junction group. Its mission was to understand why CBD preparation of CdS layers produced devices superior to those that used CdS layers prepared in other ways. For a decade, the CIS community had *known* that CBD produced the best devices. But *how* it did this remained unclear.

The Present Junction group figured out how. Performing a series of analyses—Fourier transform photoluminescence, secondary ion mass spectrometry, and X-ray photoelectron spectroscopy—the group determined that cadmium from the chemical bath penetrates the surface area of the CIS absorber and dopes it n-type. Because CIS is prepared as p-type, cadmium doping creates a shallow, buried p-n junction in the CIS.

Further, the group discovered that, with CBD, the buried junction forms within seconds after dipping in the aqueous solution; with other methods, however, it forms only on diffusion from the CdS layer. The result is that CBD induces a sharp, well-defined buried junction—which may help explain the superior quality of the devices. The Present Junction group had fulfilled its mission.

Carrying the Research Forward

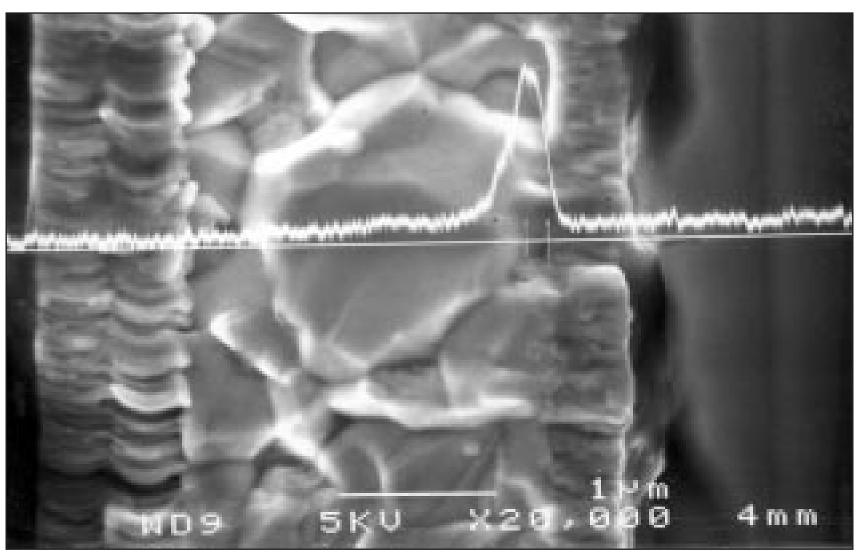
This was just the start. The results of the working group gave the NREL in-house CIS team insight on how to dope the surface area of a CIS absorber n-type and form an effective buried junction without using CdS; and thus, how to help the industrial partners of the National CIS R&D Team determine alternative ways to form a junction.

One alternative way to dope CIS is to use a zinc bath (i.e., to chemically treat the CIS layer with an aqueous zinc solution). This dopes the surface area of CIS n-type and produces a buried p-n junction. The rest of the cell structure remains the same: a substrate, a molybdenum back contact, and a transparent conducting oxide (TCO). This approach offers the twin promise of increasing device performance and simplifying device processing.

The proof is that it works. Devices processed this way have reached efficiencies as high as 14.2%. Further, it results in an approximately 10% higher short-circuit current density than comparable devices made with CdS, because it passes all the blue light through to the absorber layer.

Clearly, Ramanathan's enthusiasm is well-founded.

Continued on page 11



Rick Matson, NREL/PIX06674

For this CIS sample treated with an aqueous zinc solution, an analysis with scanning electron microscopy/electron beam induced current indicates that a well-defined buried junction has formed in the CIS about 2000–3000 Å from the TCO interface. This has implications that interest industry.

The National CdTe R&D Team—Moving

At NREL's Outdoor Test Facility, a 1-kW array of cadmium telluride modules has been silently soaking up the sun for three years. Looking at the output graphs generated by these modules offers a good reason for optimism—after three years of continual operation, array efficiency is as high as when the modules were first exposed to the sun.

This example is just part of what makes cadmium telluride (CdTe) such a promising thin-film approach. Consider the other evidence in its favor:

- Cells consistently demonstrate efficiencies between 14% and 16%. And, at 9.1% efficiency for an 8-ft^2 module, CdTe has the second highest large-area efficiency of any thin-film material.
- Efficient devices can be made with any of several different deposition techniques, including electrodeposition, close-spaced sublimation, and vapor transport.
- Three companies are in pilot production of modules. And at least one of the manufacturing options being developed by the companies—in-line, high-rate vapor transport—looks extremely promising for high-volume, low-cost production.

Warren Gretz, NREL/PIX01799

NREL field tests of a 1-kW Solar Cells, Inc., CdTe system show no output degradation over three years.

Yet, thin-film proponents are a cautious lot. When industry, academia, and laboratories formed the Thin Film PV Partnership's National Cadmium Telluride R&D Team in 1994, two concerns pervaded the membership: device stability and device efficiency. So the National Team formed two working groups to look into these concerns, a Stability working group and a High-Efficiency Device working group.

How Stable is Stable?

The industry has long had a concern with making reliable ohmic back contacts for CdTe devices. Contacting problems could result in unstable devices; therefore, the three years of stable modules as tested at NREL may not be sufficient indication of long-term stability. So, National Team members may not have been too surprised when the Stability working group cautioned that, under accelerated exposure conditions, contacting problems could result in instability, which would reduce module lifetimes.

The Stability working group had come to its conclusions cautiously and systematically. First, team members carefully set up a protocol for accelerated environmental testing of cells. Then they prepared cells with different back-contact recipes. Although the recipes differed greatly, almost without exception they used copper as the p-type dopant, a practice that is widely used by industry.

The cells were then subjected to conditions of high environmental stress (such as high temperatures) under different operating conditions (such as open-circuit voltage), and monitored for the time it took the cells' performance to degrade by 10% and 25%. These performance figures were then used to predict cell lifetimes, given real temperature data at different sites.

The group found that some cells under some conditions have predicted lifetimes as short as 3.3 years. (For other contact approaches, they found lifetimes of more than 100 years!) They also determined that short lifetime is due to failure of the back contact to retain an ohmic contact. This loss of ohmic contact may be due to either (1) the migration of copper, which would cause a loss in acceptor density in the p^+ layer, and hence a loss in the ability to transfer current, or (2) the formation of a copper oxide layer between the back contact and the CdTe, which would block the transfer of current.

News at Press Time

NREL Team Supports Hurricane Recovery

In the wake of Hurricane Georges, NREL's Byron Stafford and Holly Thomas traveled to Puerto Rico to provide emergency technical assistance in support of DOE's and NCPV's larger role of matching the PV industry's products with the needs of organizations involved in disaster prevention and response. After Georges struck the Caribbean, Jim Powell, Director of DOE's Atlanta Regional Support Office, requested NCPV's technical assistance and training with PV generators that were recently purchased for the Federal Emergency Management Agency by DOE's Federal Energy Management Program. While in Puerto Rico, the NREL team also traveled to Mona Island, a remote nature preserve, where PV is the island's primary source of power. Considering Georges' sustained wind speeds of 130 mph, the PV systems survived reasonably well. Several Puerto Ricans near the main city of San Juan had small PV systems that provided enough power for lights and TV—which was a welcome relief because their utility power was out for several weeks. Other homes and communities in the central mountains of Puerto Rico may not receive power for several months and could benefit from PV power. A newspaper article

Toward Stability and High Efficiency

If these are indeed the failure mechanisms, then alternative contacting methods must be found for those recipes that use copper. And that's one of the next steps for the working group. Members are currently preparing samples with less copper or with antimony telluride, a promising contact material that may not be subject to the suspected failure mechanisms of oxidation or migration.

A Window of Opportunity

"Devices made with almost any accepted deposition process are consistently reaching some pretty high efficiencies," said Harin Ullal, Co-Chair of the National CdTe R&D Team. "Yet, there may be some apparently simple means by which we can push the efficiencies higher."

He was talking about the task of the High-Efficiency Device working group and the changes the group is pursuing with the CdS window layer. In the typical high-efficiency device, a CdTe absorber layer is grown on a CdS/SnO_2/glass substrate, with the SnO_2 serving as a transparent conductor and the CdS forming a junction with CdTe and letting light into the absorber layer. Typically, the CdS is deposited at a thickness of about 0.2 µm (2000 Å). Such a thickness absorbs a significant percentage of the blue portion of the spectrum. The spectral response of such a device shows a high quantum efficiency only over a wavelength range from about 520 to 850 nm, with relatively little production of charge carriers in the 400-to-520-nm range. The result is that a typical device produces a short-circuit current density of only about 19 to 21 mA/cm^2.

To increase the amount of light absorbed by the CdTe absorber and hence the amount of short-circuit current generated, the working group began investigating the use of thinner CdS window layers—with thicknesses ranging from about 200 to 800 Å. The group found that thin CdS windows produce the effect sought; i.e., they allow the blue end of the spectrum into the absorber layer. This increases the generation of charge carriers, which typically increases the short-circuit current density to around 26 mA/cm^2, a jump of 25% to 30%.

All other things being equal, this would jump the device efficiency by 25% to 30%. Of course, all other things are never really equal. Problems occur if the CdS is *too* thin. At such a thinness, it is difficult to keep the deposited layer uniform in mass production. This can produce pinholes that can lead to shunting paths from the CdTe layer to the conductive oxide layer. This, in turn, reduces the open-circuit voltage. The net effect, therefore, is a compromised efficiency increase.

The working group is exploring several promising paths around this drawback. One uses a thin (1000 Å), highly resistive, tin oxide layer between the thin CdS layer and the conductive tin oxide layer. The resistive tin oxide, which acts as a barrier to shunt formation through the thin CdS, may thus help retain a high open-circuit voltage. Another approach, being developed at NREL, uses new TCOs to replace the tin oxide.

What's Next?

"We've come a long way," claimed Peter Meyers of ITN Energy Systems, the other Co-Chair of the National CdTe R&D Team. "A few years ago we thought only in terms of efficiency. It's still important to us, as evidenced by the formation of the High-Efficiency Device working group. But today we realize how important stability can be to the success of the industry. In fact, it was partly because of the industry's active interest that the National Team formed the Stability group."

"But the work of the Stability group has just begun." In fact, the group is in the first phase of its undertaking—establishing a protocol for accelerated testing.

The next step is to determine a correlation between the accelerated testing and field experience, and to determine what that correlation might imply for new modules going into the field.

Finally, the group must firmly establish failure modes and mechanisms. This, along with well-established correlations, the success of the High-Efficiency Device group, and promising manufacturing processes would help industry meet long-term national goals: low-cost, highly efficient, long-lived devices.

For more information, contact National Team Co-Chairs: Harin Ullal at 303-384-6486 or Peter Meyers at 303-420-1141.

in *The San Juan Star* two weeks after the hurricane commented that solar systems should be installed at all major intersections just to keep traffic moving when power is interrupted. Contact: **Byron Stafford, 303-384-6426**

New Management Team for NREL

On October 1, the U.S. Department of Energy announced the selection of the team of Midwest Research Institute (MRI), Battelle Memorial Institute, and Bechtel National as the management and operating contractor for NREL. MRI had held the NREL contract since the Laboratory's inception in 1977. "The new contract places an increased emphasis on bringing renewable energy technologies to the marketplace and the integration of efficiency and renewable energy with traditional energy sources, helping to ensure the nation's future energy security," said Energy Secretary Bill Richardson, who paid his first visit to NREL on October 2. Contact: **Chris Powers, 303-275-4742**

PV Web Sites Have New Look, New Usefulness

Visitors to the redesigned Web sites for the DOE Photovoltaics Program and the National Center for Photovoltaics will find much more than just cosmetic changes. The biggest improvement is a master index, a tool that promotes easy navigation within each individual site and between the two sites. Any information contained on one site is totally and transparently accessible from the other. But don't just take our word for it. Visit the sites for DOE (*http://www.eren.doe.gov/pv*) and NCPV (*http://www.nrel.gov/ncpv*) and judge for yourself. The sites are best viewed with Netscape or Internet Explorer 4.0 or higher. Contact: **Erik Nelsen, 303-384-6482**

Three Days in Denver

The Strength of U.S. Photovoltaics Ta

Three information-packed days... spirited recollections from the founding fathers of terrestrial photovoltaics... feedback from colleagues to inspire the work that lies ahead.

The tone of the NCPV Program Review Meeting held September 9–11 at the Adam's Mark Hotel in Denver was at once inspirational, optimistic, and cautionary. Yes, PV sales surmounted the $1 billion mark in 1997—for the first time ever. But speaker after speaker made it clear that there are still so many questions to answer and so much more research to be done.

Kicking Things Off

Keynote speaker James Edmonds, Chief Scientist and Technical Leader of Economic Programs at Pacific Northwest National Laboratory, had everyone's attention. "Unless solar energy is economically competitive, its role will be limited," he said. Then he demonstrated that the return on bringing down the costs of solar technologies is so great that it can justify billions of dollars spent on research.

Warren Gretz, NREL/PIX06672

PV Iron Man. *John Thornton, Larry Kazmerski, Jim Rannels, and Lloyd Herwig (from left) flank Roger Little (center) of Spire Corporation, winner of the Paul Rappaport Award recognizing service in the field of photovoltaics. Herwig himself was the first Rappaport winner, having won in 1996.*

Jim Rannels, Acting Director of DOE's Office of Photovoltaic and Wind Technologies, spoke about the R&D links to commercialization. "Now we have achieved about a two-lane bridge to the 21st century... with two more lanes under construction. The product and technology have evolved, and costs have come down. The price has relentlessly yielded to the efforts of folks such as yourselves."

The next presenter was Roland Hulstrom, Acting Director of the National Center for Photovoltaics. "Promoting partnering and growth opportunities is part of our mission," said Hulstrom, as he displayed a list of the NCPV's 107 active partners. He then introduced the NCPV contract staff, commending their work in awarding nearly 100 subcontracts valued at $25 million in a compressed schedule of about 8 months.

Honoring the Past

Lloyd Herwig and Richard Blieden carried the audience back to 1973 in Cherry Hill, New Jersey, with an insider's look at the first PV conference to focus on terrestrial technologies and applications. It was fitting that the 25th anniversary of Cherry Hill was commemorated at the Review Meeting, because this conference planted the seed for the U.S. PV Program.

A highlight of the first morning's session was Roger Little of Spire Corporation winning the Paul Rappaport Award, which recognizes outstanding service in the field of photovoltaics. Spire could also win an award for PV-industry longevity, having been established in 1969. By way of introduction, Larry Kazmerski praised Little's persistence, calling him one of PV's foremost friends. "Roger is the perfect PV device. His 'active area' matches his total area—the man has no body fat!" said Kazmerski.

Like the triathlete he is, Little responded in kind. "At the Iron Man in Hawaii, in the midst of the lava fields, you can really appreciate the power of the sun. Your day goes from 7:00 a.m. to 7:00 p.m.—at the end it's dark and you run on battery power."

Present R&D Status

There followed two solid days of oral presentations and poster sessions, on topics covering the whole of the PV Program from the laboratory to the marketplace. The meeting was a showcase for research progress on thin films and crystalline materials, and for achievements in the laboratory and the field involving characterization, components and systems, markets and applications, and PV manufacturing. Eight technical and two poster sessions were well attended by the 257 meeting participants, with some traveling from Japan, Germany, Italy, Israel, and Sweden. All told, there were 48 technical oral presentations and 83 poster presentations.

Warren Gretz, NREL/PIX06670

The "Cherry Hill Five." *No, this isn't a new rap group performing on the streets of Denver. It's Tom Surek, Richard Blieden, Larry Kazmerski, Alan Fahrenbruch, and Lloyd Herwig (from left), all of whom participated in the Cherry Hill conference in 1973.*

The breadth of the U.S. PV Program—including university, industry, and national laboratory contributions—was on display, as the following examples demonstrate. Al Compaan of the University of Toledo reported on the effectiveness of several types of laser-scribing on seven types of thin-film materials. Rick Powell of Solar Cells, Inc., described that company's success with high-throughput manufacturing and long-term stability testing of cadmium sulfide/cadmium telluride PV modules. James Gee, who also served as meeting Co-Chair, summarized recent progress at Sandia National Laboratories in the development of back-contact crystalline-silicon solar cells and modules (wherein optimization of the process sequence has allowed cell efficiency improvements from around 12% to 17% in the past year). And NREL's Carl Osterwald reported on the extensive module-testing capabilities at the Outdoor Test Facility; in the near future, environmental stress testing will begin on the PV portions of several building-integrated PV products, including curtain walls, skylights, small inverters, and PV/thermal hybrids.

Warren Gretz, NREL/PIX06671

A Perfect Poster. *Pat Dippo and Dick Ahrenkiel put the finishing touches on "Injection-Level Spectroscopy of Impurities in Photovoltaic Materials," one of 83 posters presented at the meeting.*

PV Now and in the Future

Tom Surek, Technology Manager for NREL's PV Program, has spoken at all 15 Review Meetings. He led off the final session by asking the questions: "Where are we? Where do we stand in relationship to the rest of the world?" Based ultimately on his own analyses and biases, Surek awarded the United States a clear lead in non-ingot crystalline silicon (where 25 years of research is paying off!), thin-film cadmium telluride, and testing and standards. He said we still have an edge in thin-film amorphous silicon, thin-film copper indium diselenide (but there are increasing efforts in the Pacific Region and Europe), and high-efficiency devices and concentrators.

The race is too close to call in other areas, with a dead heat in crystalline silicon ingots and materials characterization (a former U.S. stronghold, but Europe is rising). In the area of new ideas, the Pacific Region (mainly Japan and Australia) has the lead (spurred by increased funding), with Europe and the U.S. trailing behind. Balance of systems and in-country marketing are European strengths. Overall, said Surek, "I'm fairly impressed with the U.S. effort. We're lacking in domestic markets, but are competitive in international markets. We have a strong R&D program, but I'm worried about the innovation gap."

James Wilkie, Solar Technology Manager with the Shell Group, spoke of a major recent development within that company that creates a framework for rapid expansion: the establishment of Shell International Renewables Ltd. "We have an investment commitment of up to $500 million dollars—a lot for the renewables area—and have been given wide latitude to experiment and initiate," he said.

Shell's activities include a major commercial initiative in South Africa that supplies PV electricity under a "fee for service" scheme, which features "debit" cards that are prepaid at a local general store. Shell has also equipped some of its service stations in Japan with backup solar power to fuel relief efforts after earthquakes.

Wilkie likes the chances for a strong PV industry in the future. He conceded that much of the industry still depends on subsidies, and that the pace of PV technology implementation is not as far along as many thought it would be, but, at Shell, "We see the potential for extraordinary growth for the PV industry and for renewables in general."

This echoed the sentiments of General Chair Mowafak Al-Jassim in his remarks that opened the meeting two days earlier. "With the wealth of R&D results being reported at this year's conference, the PV industry should continue to grow at an increasing rate, so that the next jump to $2 billion of PV systems sales—double today's level—should come quite soon," he said. "The dream of the Cherry Hill participants, of a mature, commercially successful PV industry that helps to provide power to us on Earth, is being realized—thanks to you."

Warren Gretz, NREL/PIX06669

The Gracious Host. *General Chair Mowafak Al-Jassim made sure everyone was comfortable and well-fed. Here he discussed the day's events with Ranji George of South Coast Air Quality Management.*

For additional information, contact: Mowafak Al-Jassim, 303-384-6602.

NREL PV researchers and managers interact with industry on several levels. Although we freely share our research results and the nonproprietary results of our subcontractors, many of our interactions involve the exchange of confidential information, including the results of certain measurements. The following are some notable recent interactions.

NREL's Outdoor Test Facility (OTF) has a new addition: it's a 1.2-kW_{dc} PV Roofing Shingle System from **United Solar Systems Corp.**, Troy, MI. The system features 72 triple-junction amorphous silicon SHR-17 roofing modules (each rated at 17 watts at Standard Test Conditions), configured in 12 parallel strings, and connected to a Trace 4048PV grid-tied inverter. A data acquisition system monitors irradiance, array and air temperature, system ac and dc voltage, current, and power. This system of commercially available modules replaces a previous United Solar prototype roofing system. The new shingle system is installed directly onto the roof and takes the place of asphalt shingles. Staff at the OTF will monitor system performance and reliability for several years, which will help United Solar validate the performance of its new triple-junction amorphous silicon technology. This work will help to develop confidence in the performance and reliability of the integrated PV roofing product and help commercialize this thin-film technology. Contact: **Ben Kroposki, 303-384-6170**

At a recent Industry Growth Forum in New York City, **NREL** joined with its industry partners to spread the word about photovoltaics and other renewables. The goal of these periodic forums organized by NREL is to strengthen the working relationships between the investment community and renewable-energy-related businesses. Twelve companies, including many NREL subcontractors under the PV Program, made presentations to a panel of business and finance experts, including utility investment managers. Presenters included **Architectural Photovoltaic Glass**, **Ascension Technology**, **Atlantis Energy, DayStar Technologies**, **Energy Photovoltaics, International Solar Electric Technology**, **ITN Energy Systems**, **SAGE Electrochromics**, **Sundye, Sun Systems**, **SUN Utility Network**, and **SunWize Technologies**. Most of the presentations concerned PV module manufacturing, innovative PV systems and marketing approaches, and building-integrated PV products. The presenters received valuable inputs on their business plans and approaches for presenting their plans to venture-capital interests. After the Forum, NREL's **John Thornton** led a tour of the Cooper-Hewitt National Design Museum's newest exhibit, "Under the Sun: An Outdoor Exhibition of Light." Contact: **Tom Surek, 303-384-6471**

GT Equipment Technologies, Inc. (GTi), Nashua, NH, and **NREL** collaborated recently on a silicon materials project. GTi received a Small Business Innovative Research (SBIR) grant to grow polycrystalline silicon feedstock by chemical vapor deposition on tubular silicon substrates, with the goal of improving the deposition rate. GTi was unable to find a commercial source to furnish the Si tubes, and asked NREL for help in demonstrating the feasibility of its SBIR concept. In collaborative work, crystal-growth hot-zone parts were designed, and detailed drawings were generated at NREL. GTi then manufactured these parts to specifications and sent them to NREL, where **Ted Ciszek** and colleagues grew 20-mm-diameter Si tubes using a capillary-action shaping technique. **Colorado School of Mines** student **Joe Dodds** assisted, having chosen this as his senior design project. **Mohan Chandra** (GTi R&D Manager) and **Ijaz Jafri** (GTi R&D Projects Engineer) visited NREL in late June to observe the first growth experiments and to discuss further potential areas of collaboration. Contact: **Ted Ciszek, 303-384-6569**

A solar sunroof donated by **Solarex Corporation**, Frederick, MD, was installed in a 1997 Chrysler Breeze for an experimental PV application in the operation of interior cooling fans and other devices (which will be used to keep the interior of the vehicle cool). In conjunction with this event, **NREL's Lorenzo Roybal** led tours through the **OTF** and the **Solar Energy Research Facility** for project participants from **Chrysler**, **Johnson Controls, Inc.** (JCI), **Pittsburgh Plate Glass** (PPG), and **Life Enhancement Technologies**. The PV sunroof is attractive because it generates power for required loads without discharging the starter battery. PPG is still interested in PV windshields, but under low priority. The Chrysler, JCI, and PPG partnership will continue to work together to further develop a "cool car," which may include PV. Contact: **Lorenzo Roybal, 303-384-6489**

BP Solar, Fairfield, CA, has fabricated several thin-film CdTe power modules in its Fairfield facilities, the first the company has produced in the United States. The module size is typically 14 x 44 inches and has a power output of 25 to 30 W. The module structure is glass/SnO_2/CdS/CdTe/metal. The tin-oxide-coated glass is purchased from **Libbey-Owen-Ford**, Toledo, OH. The CdTe layer (1.6 µm) is electrodeposited, whereas the CdS film (0.1 µm) is chemical-bath deposited. At September's **National CdTe R&D Team** Meeting (held in conjunction with the **NCPV Program Review Meeting**), BP Solar reported that the modules have proven stable over several months of testing. This is a good starting point for BP Solar's thin-film CdTe PV technology, as it fine tunes its manufacturing facilities at Fairfield to 3 MW in the next few years. Contact: **Harin Ullal, 303-384-6486**

NREL has verified a thin-film CIS-based minimodule (74 cm^2) with an aperture-area efficiency of 7.95%. The minimodule was fabricated by **International Solar Electric Technology** (ISET), Inglewood, CA. The mini-

Continued on page 10

Subcontracts

Subcontracted research with universities and industry, often cost-shared, constitutes an important and effective means of technology transfer in NREL's PV Program. From October 1997 through September 1998, we awarded nearly 100 new subcontracts (examples listed below) totaling more than $25 million. For further information, contact Ann Hansen (303-384-6492).

Energy Conversion Devices (6/98–8/01)
Efficiency and Throughput Advances in Continuous Roll-to-Roll a-Si Alloy Manufacturing Technology
$3,000,000 (NREL) $4,343,285 (cost share)

Siemens Solar Industries (6/98–8/01)
Specific PVMaT R&D on Siemens Cz Silicon Product Manufacturing
$2,997,625 (NREL) $2,997,623 (cost share)

Global Solar Energy (7/98–9/01)
Photovoltaic Manufacturing Cost and Throughput Improvements for Thin-Film-Based CIGS Modules
$2,671,863 (NREL) $1,013,797 (cost share)

ASE Americas (8/98–10/01)
Cost Reductions in High-Volume EFG PV Module Manufacturing Line
$2,930,506 (NREL) $3,767,254 (cost share)

International Solar Electric Technology (6/98–6/01)
CIS-Type PV Device Fabrication by Novel Techniques
$1,950,000 (NREL) $195,000 (cost share)

Omnion Power Engineering Corp. (7/98–1/00)
Manufacturing and System Integration Improvements for One- and Two-Kilowatt Residential PV Inverters
$96,000

Weizman Institute of Science (7/98–7/01)
Identifying and Overcoming Degradation Mechanisms in CdTe Solar Cells
$405,000

Iowa State University (7/98–7/01)
Research on Improved Amorphous Silicon and Alloy Materials and Devices Prepared Using ECR Plasma Techniques
$701,000

University of Florida (7/98–7/01)
Future CIS Manufacturing Technology Development
$810,000

University of Illinois (7/98–7/01)
Properties of Wide-Gap Chalcopyrite Semiconductors for Photovoltaic Applications
$139,500 (NREL) $270,000 (EPRI funding)

NIST (7/98–7/01)
Characterization of Small Particle Formation in the Preparation of Amorphous Silicon Solar Cells and Determination of the Electric-Field Profile in Solar Cells Using Scanning Tunneling Microscopy
$345,000

Publications

Dissemination of research results is an important aspect of technology transfer. NREL researchers and subcontractors publish some 300 papers annually in scientific journals and conference proceedings, as exemplified by the recent publications listed below. PV program and subcontractor reports are available from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161. For further information, contact Ann Hansen (303-384-6492).

Ahrenkiel, R.K.; Johnston, S. "Contactless Measurement of Recombination Lifetime in Photovoltaic Materials." *Solar Energy Materials and Solar Cells*. 1998; 55; pp. 59–73.

Basol, B.M., et al. *Application of CIS to High-Efficiency PV Module Fabrication: Phase 3 Final Technical Report*. August 1998; 25 pp. NREL/SR-520-25218. Work performed by International Solar Electric Technology, Inglewood, CA.

Coutts, T.J.; Fitzgerald, M.C. "Thermophotovoltaics." *Scientific American*. September 1998; 279(3); pp. 68–73. NREL/JA-520-25203.

Friedman, D.J., et al. "1-eV GaInNAs Solar Cells for Ultrahigh-Efficiency Multijunction Devices." *World Conference on Photovoltaic Solar Energy Conversion, 6–10 July 1998, Vienna, Austria*. NREL/CP-520-23874.

Gordon, R.G., et al. *Optimization of Tranparent and Reflecting Electrodes for Amorphous Silicon Solar Cells, Final Technical Report*. September 1998; 36 pp. NREL/SR-520-25424. Work performed by Harvard University, Cambridge, MA.

Making the Connection: Key Issues in Connecting a Photovoltaic System to the Utility Grid. Brochure; June 1998. DOE/GO-10098-523.

McNutt, P., et al. *Interim Test Methods and Procedures for Determining the Performance of Small Photovoltaic Systems*. July 1998; 24 pp. NREL/TP-520-25077.

NREL Photovoltaic Program FY 1997 Annual Report. June 1998; 564 pp. NREL/BK-210-23607.

Powell, R.C., et al. *Technology Support for Initiation of High-Throughput Processing of Thin-Film CdTe PV Modules*. September 1998; 85 pp. NREL/SR-520-25422. Work performed by Solar Cells, Inc., Toledo, OH.

Rummel, S., et al. "PV Cell and Module Performance Measurement Capabilities at NREL." *NCPV Program Review Meeting, 8–11 September 1998, Denver, Colorado*. NREL/CP-520-25411.

Sopori, B.L., Chairman. *Eighth Workshop on the Crystalline Silicon Solar Cell Materials and Processes: Extended Papers and Abstracts from the Workshop, 17–19 August 1998, Copper Mountain, Colorado*. 1998; 261 pp. NREL/CP-520-25232.

University Corner

In one way, the **Sunrayce 99** competition has already begun. Three schools—**Clarkson University**, **Iowa State University**, and **MIT**—won $9,000, $7,000, and $5,000, respectively, for submitting the top three proposals. And even though the proposal phase is complete, schools have until January 1999 to enter the race. Sunrayce Headquarters has moved from the Detroit area to the DOE Atlanta Support Office. Atlanta will be one of the overnight stops on the race route that is basically from Washington, D.C., through Atlanta, to Orlando, FL, where EPCOT Center will host the finish.

From June 21–30, the proposed Sunrayce 99 route was tested with solar cars to assess the technical difficulty, develop community relations, and generate media interest. The test run started at the DOE Forrestal Building on Sunday, June 21, and ended at EPCOT in Orlando, June 30. Overnight stops along the way included Winchester, VA; Lynchburg, VA; Raleigh, NC; Charlotte, NC; Clemson, SC; Atlanta, GA; Macon, GA; Tallahassee, FL; and Ocala, FL. The Sunrayce 97 solar car from **Rose-Hulman Institute of Technology** completed the entire route on solar only. Three other solar cars from Clarkson University, **Ohio State University**, and **Drexel University** ran small portions of the route and were on display. Four other teams sent representatives to gather first-hand information and provide feedback to the route manager. Based on the feedback from the organizers and the teams, the first two days were changed so that now the route goes from Washington, DC, to Charlottesville, VA, and then on to Raleigh, NC. The revised route will present a good challenge for the top teams with two back-to-back days of 200 miles each, and several short days where every team can look good. Contact: **Byron Stafford, 303-384-6426**

The objective of the **University PV Research Equipment** Request for Proposal, which closed on June 1, was to fund the acquisition of critical PV research and test equipment at universities participating in the **NREL/DOE PV Program**. After reviewing and ranking the proposals, NREL awarded a total of $1,061,135 for 17 university subcontracts during July and August. The universities provided a total of $350,984 in "price participation" (called "cost-sharing" in the case of industry subcontracts) from other funding sources to supplement their awards. The awards are listed below:

Arizona State University	$66,932
California Institute of Technology	23,875
Clemson University	94,472
Colorado School of Mines	83,000
Georgia Institute of Technology	60,670
North Carolina State University	100,000
Pennsylvania State University	50,245
State University of New York–Buffalo	32,935
Syracuse University	16,615
University of Delaware (IEC)	100,000
University of Florida	91,000
University of Oregon	45,787
University of S. Florida (Group 1)	97,913
University of S. Florida (Group 2)	50,000
University of Toledo	49,225
University of Utah	49,280
Washington State University	49,156
Totals	**$1,061,135**

These subcontract awards are expected to bolster university research equipment infrastructure by replacing or updating old equipment—10 to 15 years was not an unusual equipment age—thereby benefiting research on various projects within the NREL/DOE PV Program. Contact: **Robert McConnell, 303-384-6419**

Industry Update, Continued from p. 8

module parameters are V_{oc} = 7.53 V, J_{sc} = 1.7 mA/cm^2, and FF = 0.616. There are 18 cells that are monolithically connected in series using laser and mechanical scribing techniques. The minimodule structure is ZnO/CdS/CIS/Mo/glass. ZnO is deposited by metal-organic chemical vapor deposition, CdS by chemical-bath deposition, CIS by a proprietary nonvacuum method, and Mo by sputtering. Low-cost soda-lime glass is used as the substrate. This new result will help ISET engineers improve submodule performance as they scale up their thin-film, CIS-based, pilot-line manufacturing, as part of the company's work with the **Thin Film PV Partnership Program**. Contact: **Harin Ullal, 303-384-6486**

Public Service Company of Colorado now has the first net-metered PV system in Colorado. A **United Solar** PV-integrated, standing-seam metal roof was installed at the new **Big Horn Center** in Silverthorne, CO, in mid-September. Two 1-kW$_p$ systems, each comprising 18 nine-foot-long panels, are expected to meet about 10% of the building's load. Educational kiosks will describe the PV system and inform the public about energy-saving appliances and products they can purchase at the Big Horn Center (a building material/home improvement center). Installation of the PV system and energy-efficient features in the building was accomplished with technical assistance from **NREL** through the Domestic Markets Task (**Christy Herig**), the PV for Buildings Task (**Sheila Hayter**), and the Exemplary Buildings Program (**Paul Torcellini**). As a result of the Exemplary Buildings Program's participation in the project, additional energy-efficiency features, such as an improved building envelope and daylighting design and controls, will be incorporated into the project's next phase of construction planned for spring of 1999. Contact: **Christy Herig, 303-384-6546**

NREL has verified a world-record 11.8%-efficient thin-film CIGSS monolithic module (3651 cm^2) fabricated by **Siemens Solar Industries** (SSI), Camarillo, CA. The corresponding power output is 43 W. This is the highest efficiency for any thin-film module in the world (of any size) and approaches that of conventional silicon PV technology. There are 30 power modules, all of whose efficiencies were verified in the range of 10.9% to 11.8%, with power output of 39 to 43 W. These modules will be deployed in a 1.2-kW array at NREL's **OTF** for long-term outdoor stability testing. The array efficiency is expected to be around 11%. This significant result indicates that thin-film PV can achieve efficiencies that are competitive with conventional Si-based PV technology. It will also help SSI as it scales up its thin-film CIGSS manufacturing process, as part of the **Thin Film PV Partnership Program**. Contact: **Harin Ullal, 303-384-6486**

Continued on page 11

Success Stories, Continued from p. 3

Diffusion Solution

In a sharply contrasting style, Bulent Basol of International Solar Electric Technology (ISET) calmly intoned, "Yes. I think ISET benefited from the exercise. In fact, I think all the group members benefited."

He was talking about the working group (which included NREL, the University of Illinois, and the companies of ISET, Energy Photovoltaics, and Lockheed Martin) that was formed to investigate the role of the molybdenum back contact in the diffusion of sodium from soda-lime glass substrates into the CIS absorber layer.

The companies were concerned about the role of molybdenum. It could either retard or enhance the diffusion of sodium, depending on the source of the molybdenum and its thickness. This showed up in the efficiencies of cells. All other parameters being held constant, cells made with different molybdenum exhibited different efficiencies.

So the companies, while protecting their proprietary information, cooperated to investigate molybdenum's role. The group found several interesting things:

- First, the diffusion of sodium into CIS is not a strong function of the molybdenum itself. Rather, it is a function of the growth method used for the CIS layer; the chemistry at the surface of the CIS film determines the attraction for the sodium.
- Second, some sodium diffusion is good for a CIS device and enhances the performance. But how much is good also depends on the process for making the CIS layer.
- Third, there is a relationship between the sodium content and the adhesion of the CIS to the molybdenum contact layer, a relationship that also depends on the CIS processing.

The upshot of this research is that there is no single way to optimize a device vis-à-vis sodium diffusion. Rather, because different groups use different CIS growth techniques, each company must determine for itself how it will use the knowledge gained to optimize its devices.

ISET used the information garnered through the group's research to reduce the thickness of the molybdenum layer by 80%, allow appropriate sodium diffusion, and improve adhesion of the CIS layer to the molybdenum. The company then applied the added knowledge to its new, inexpensive, non-vacuum process.

In Industry's Interest

In April of this year, the National CIS R&D Team reorganized again. It was clearly time to refocus the talents of the researchers to specific concerns of each of the team's industry members and to apply the successes of the previous working groups. As Rommel Noufi, Co-Chair of the National Team along with Harin Ullal, explained, "I have always believed that to achieve breakthroughs and to solve problems, you should have clear objectives, set clear priorities, and adhere to a timetable. Our successes should have an impact on industry's efforts to commercialize the technology—which is part of NREL's mission."

Today, under the new CIS team structure, ISET leads a group that works on issues associated with the company's new process, including ways to incorporate sulfur and gallium into the absorber layer to increase open-circuit voltage and efficiency.

Energy Photovoltaics heads a second group investigating the junction formation between reactively deposited ZnO and the CIS absorber layer—a field of research that certainly may be enhanced by the junction investigations performed by the previous groups.

A third group is helping Global Solar Energy figure out how to deposit a good, reproducible CIGS absorber layer on a flexible polymer substrate. This is an innovative concept that has already benefited from federal CIS research by using NREL's coevaporation process, and that may derive further benefits through the company's pending collaboration with NREL on the zinc-bath doping approach.

A fourth group is being headed by a brand new industrial member of the National CIS Team—UNISUN. Using funding from the Small Business Innovative Research program, the company is investigating a novel method for CIS processing. UNISUN has achieved device efficiencies of up to 9%; with the help of its working group, the company hopes to bring efficiencies up to par with those attained through conventional growth techniques.

A fifth group further explores the cause of, and solutions to, transient effects. Because this primarily is a concern that Siemens Solar Industries has with some of its modules, the company is leading the investigation. In fact, Siemens has recently made progress toward reducing the transient effects, as reflected by its entry into limited production of large-area CIS modules—a major milestone in the development of the CIS technology.

Current Collaborations

And the work done on buried junctions and the zinc-bath treatment? The new approach still needs to be improved to where the performance of devices made with it are equal to that of CdS/CIS devices made with CBD. Nonetheless, two of the National CIS Team's industrial members—Siemens Solar and Global Solar Energy—are quite interested. They are forming collaborations with the NREL CIS team to see if the approach can be adapted for their production processes.

For more information, contact National Team Co-Chairs: Harin Ullal at 303-384-6486 or Rommel Noufi at 303-384-6510.

Industry Update, Continued from p. 10

Participants from **DOE**, **NREL**, and numerous U.S. PV companies participated in a workshop on the use of small PV and wind technologies for rural electrification in China. Held in Beijing, China, on September 16–18, the workshop objectives were to: provide information to U.S. and Chinese businesses on rural electrification opportunities and plans for China; provide a forum to facilitate networking of U.S. and Chinese company representatives; and develop a strategy for fostering U.S./Chinese joint-venture and other business activity in rural and remote renewable energy electrification in China. More than 70 Chinese and U.S. business, government, and NGO representatives attended. U.S. participants included **Solarex**, **Siemens Solar Industries**, **ASE Americas**, **Energy Photovoltaics**, **United Solar/Energy Conversion Devices**, **Ascension Technology**, **WINROCK**, **Bergey Wind Company**, **Atlantic Orient Company**, **Solar Electric Light Fund**, and **Solar Electric Light Company**. In addition, more than 15 Chinese business representatives attended. One significant outcome was that the U.S. and Chinese delegations agreed that they must act together to change the environment that inhibits the ability of U.S. companies to conduct business in China and that deprives Chinese companies of the benefits of U.S. technology and business expertise. The Chinese participants were unanimous in their request for U.S. technology and products, and training in technology and business. Both the U.S. and Chinese participants want to move forward in expanding business activities in China. All agreed that workshops such as this are an important mechanism for fostering U.S.-Chinese business partnerships. Contact: **Dave Renné, 303-275-4648**

PV Calendar

January 23–29, 1999, *Photonics West, Showcasing the Power of Light*, Sponsor: SPIE—The International Society for Optical Engineering. Location: San Jose, CA. Contact: Roberta Hart. Phone: 360-676-3290. Web site: *www.spie.org/info/pw*

February 10–13, 1999, *World Renewable Energy Congress 1999*. Location: Perth, Western Australia. Contact: Dr. Kuruvilla Mathew. Phone: +61.8.9360.2896, Fax: +61.8.9310.4997.

April 5–9, 1999, Materials Research Society Spring Meeting. Sponsor: MRS. Location: San Francisco, CA. Contact: MRS Headquarters. Phone: 724-779-3003. Web site: *www.mrs.org/meetings/spring99/cfp/contents.html*

April 12–16, 1999, *The 26th International Conference on Metallurgical Coatings and Thin Films*. Sponsor: American Vacuum Society. Location: San Diego, CA. Contact: Mary S. Gray. Phone: 703-266-3287. Web site: *www.vacuum.org/icmctf/icmctf.html*

April 17–22, 1999, *SOLTECH '99*. Sponsors: SEIA, IREC, UPVG, HSEIA. Location: Kansas City, MO. Contact: Linda Ladas, SEIA. Phone: 202-383-2601. Web site: *www.seia.org/main.htm*

May 2–7, 1999, *Electrochemical Society 195th Meeting*, including *Photovoltaics for the 21st Century* (Symposium K3). Sponsors: ECS, NREL. Location: Seattle, WA. Contact: Robert McConnell, NREL. Phone: 303-384-6419. Web site: *www.electrochem.org/meetings/195/symp.html*

June 13–16, 1999, *Solar 99: Growing the Market*. Host: The American Solar Energy Society. Sponsors: U.S. Department of Energy, Northeast Utilities, New England Electric System. Location: Portland, ME. Contact: Becky Campbell-Howe. Phone: 303-443-3130. Web site: *www.sni.net/solar/solar99/main.htm*

July 4–9, 1999, *ISES 1999 Solar World Congress*. Sponsor: International Solar Energy Society. Location: Jerusalem, Israel. Contact: ISES Secretariat. Phone: 972-3-5140000. Web site: *http://tx.technion.ac.il/~meryzse/ises99.html*

This quarterly report encourages cooperative R&D by providing the U.S. PV industry with information on activities and capabilities of the laboratories and researchers at NREL.

Robert McConnell........303-384-6419
PV Program Communications

Tom Surek.....................303-384-6471
Technology Manager, Photovoltaics

Susan Moon...................303-384-6631
Editor

Gary Cook.....................303-275-3659
Writer

Jim Miller......................303-384-6595
Graphic Designer

NREL Report No. BR-520-25282. NREL is a national laboratory operated for the U.S. Department of Energy under Contract No. DE-AC36-83CH10093.

NREL

PV Program
1617 Cole Blvd. Golden, CO 80401-3393

If you are not on the mailing list for this publication and would like to receive it, please send your name, affiliation, and address to the NREL address listed above left.

Printed with a renewable source ink on paper containing at least 50 percent wastepaper, including 20 percent postconsumer waste